SPECTRAL AND STATISTICAL ANALYSES OF AMBIENT NOISE IN SPITSBERGEN FJORDS AND IDENTIFICATION OF GLACIER CALVING EVENTS

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1 INTRODUCTION

Climate warming is particularly well observed in the Arctic, where average temperatures have risen in some areas by more than 2°C since the 1950s [1]. The area of permanent sea ice and its thickness are decreasing at rapid rates. Tidewater glaciers also retreat faster than those terminating on land. These glaciers are increasingly important because their rapid calving directly influences the potential for accelerated sea level rise.

Ice activity is a predominant contributor to underwater ambient noise in the Arctic Ocean. The physical processes accompanying melting glaciers generate underwater sound audible in the fjords of marine-terminating glaciers, and these are potentially useful in the study of their changing dynamics. The noise generated by glaciers allows for the quantification of melting processes even in the absence of direct observation (usually visual and from the surface) and can be a good indicator of rapid climate changes. Detection and analysis of hydro-acoustic signals from a glacier will provide a valuable method to predict the effects of global warming on the Earth's environment. The results contribute to a better understanding of the stability of ice shields under the stress of rising ambient temperatures. The study of ambient noise in the Arctic has a long history [e.g. 2, 3, 4, 5 and references therein], but the literature on this subject is not very extensive.

In this study we present results of underwater ambient noise measurements, which were carried out in Spitsbergen in 2009, at Hornsund Fjord, surrounded by melting glaciers. Measurements were conducted at frequencies from 20 Hz to 24 kHz using an omnidirectional hydrophone deployed 18 meters deep [6]. Calm weather conditions during the experiment enabled measurements without noise coming from wind, rain or breaking waves. Our previous work [6] was focused on detection of melting and calving events in recorded ambient noise signals. The spectral, wavelet, fractal and statistical parameters of noise computed in a sliding window were the input to a neural network algorithm, which classified ambient noise into three different groups of signal events. However, some events were difficult to classify correctly and reliably. This fact inspired us to search for more sophisticated statistical analyses, which could deliver trustworthy information on the occurrence of calving events in acoustical measurements. We put forward the hypothesis that, at low frequencies, the probability density distribution of the noise significantly differs from the normal distribution and gives clues about the number and diversity of contributing sources.

2 MEASUREMENT METHODOLOGY

Measurements were carried out during the Arctic expedition organised by Gdynia Maritime University in August 2009, on board R/V *Horyzont II*. Hornsund Fjord is surrounded by mountains and melting glaciers, which are especially frequent in the inner part – the Brepollen area. During measurements, the weather was calm, with no wind, no atmospheric precipitation, no breaking waves, but fast currents of water flowing from the marine-terminating glaciers. Furthermore, during ambient noise measurements, the fjord was completely empty of vessels (R/V *Horyzont II* was anchored more than 10 km from the measurement points). Such "clean" experimental conditions allow for registration of ambient noise coming mainly from melting glaciers, melting icebergs and growlers.

Measurements of underwater ambient noise were conducted from a small rubber boat using an omnidirectional hydrophone ITC-6050C, deployed 18 meters deep. Recordings were carried out in the frequency range 20 Hz – 24 kHz using a digital recorder Sony DAT TCD-D8 sampling at 48 kHz and with 16 bit quantization. The sensitivity of the hydrophone is nearly flat in the measurement range and equals -157 dB re 1V/μPa. The ambient noise signal was amplified with a constant gain of 19 dB. At the beginning and end of each recording session (~2 hours long), one minute of white noise was recorded for calibration purposes. To account for the strong currents and the drift of the measurement boat, GPS positions were recorded every several minutes. Video and photographic records were obtained throughout the measurements. In the Brepollen area, two 360° panoramic photographs were taken, which were helpful in glacier identification. A satellite image (Landsat 7, ETM+ sensor) was also used for data analysis of the changing glaciers barrier in Brepollen.

3 DATA PROCESSING AND RESULTS

The main goal of the data processing effort was to identify predominant noise sources and their statistical features, with a particular emphasis on calving glacier and cracking events. According to our previous results, published in [6], noise spectrum levels (NSLs) for Hornsund Fjord are significantly different from the typical ambient noise levels in the open ocean (Fig. 1), with the most visible differences at low frequency ranges. A distinct increase of NSL (especially below 300 Hz) during the first 20-40 minutes of recordings in the Brepollen area was the result of a big calving event observed at the Stor glacier wall (green curve in Fig. 1).
This allowed us to hypothesize that, at low frequencies, the probability density distribution of the ambient noise significantly differs from the normal distribution and gives clues about the number and diversity of contributing sources, especially connected with calving glacier and cracking events.

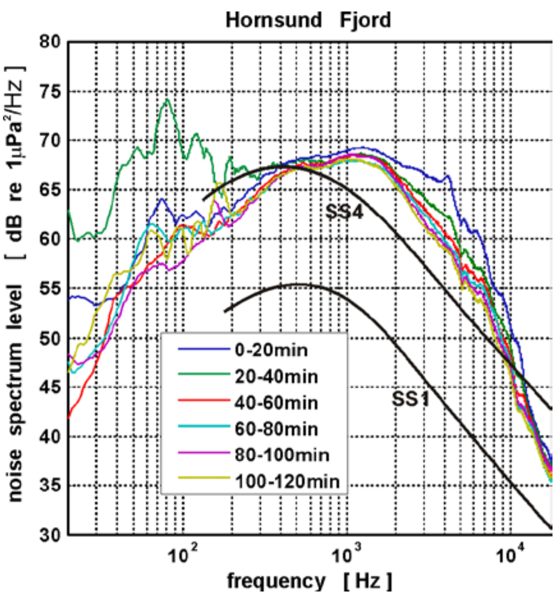

Fig.1 Noise spectrum levels [dB re $1\mu Pa^2/Hz$] calculated from one-second time segments and averaged over 20-minutes time periods, recorded in Hornsund fjord, in the Brepollen area close to the Stor glacier [6]. The black curves labeled SS1 and SS4 indicate the expected noise spectrum levels for Sea States 1 and 4 (Beaufort scale) in the open ocean [7].

At the first stage, the goodness-of-fit hypothesis test was performed in order to determine if the noise data have a standard normal $N(0,1)$ distribution function. For this purpose, the Kolmogorov-Smirnov test, the χ^2-test and additionally the Jarque-Bera test [8] were applied on 1-second time intervals of noise pressure time series, previously filtered in 1/3rd-octave bands chosen with central frequencies F_c= [50 100 1000 2500 5000 10000] Hz, in order to check if their distribution is frequency-dependent.

These tests show that, in a mid- and high-frequency range (f > 2.5 kHz), for approximately over 85% of data, the null hypothesis cannot be rejected at the 5% significance level and in such a way it demonstrates a central-limit type behaviour. It can be explained that, at the high frequencies, the bubbles released from melting ice dominate as a main acoustic source contributing to the ambient noise. Moreover, the high frequency components of the noise field come mainly from local sound sources, which cannot be generally related to the glacier.

In turn, at the lower frequencies, there is also an observable broadening of the spectrum due to the appearance of a low-frequency noise component generated by mechanical vibrations associated with calving ice at the glaciers. This allows us to limit data analysis to the particularly interesting range of low frequencies below 1 kHz, where power spectral densities were estimated.
Examples of a one-minute noise pressure time series (filtered in a frequency range from 28 Hz to 1,118 Hz), containing the large event of a calving glacier (a) and its spectrogram (b), are presented in Fig. 2. This particular event also is visible in Fig.1 (green curve) as a significant change of noise spectrum level during the first 20 to 40 minutes of the experiment (up to 17 dB louder at 80 Hz, compared to the relatively quiet conditions at the time).

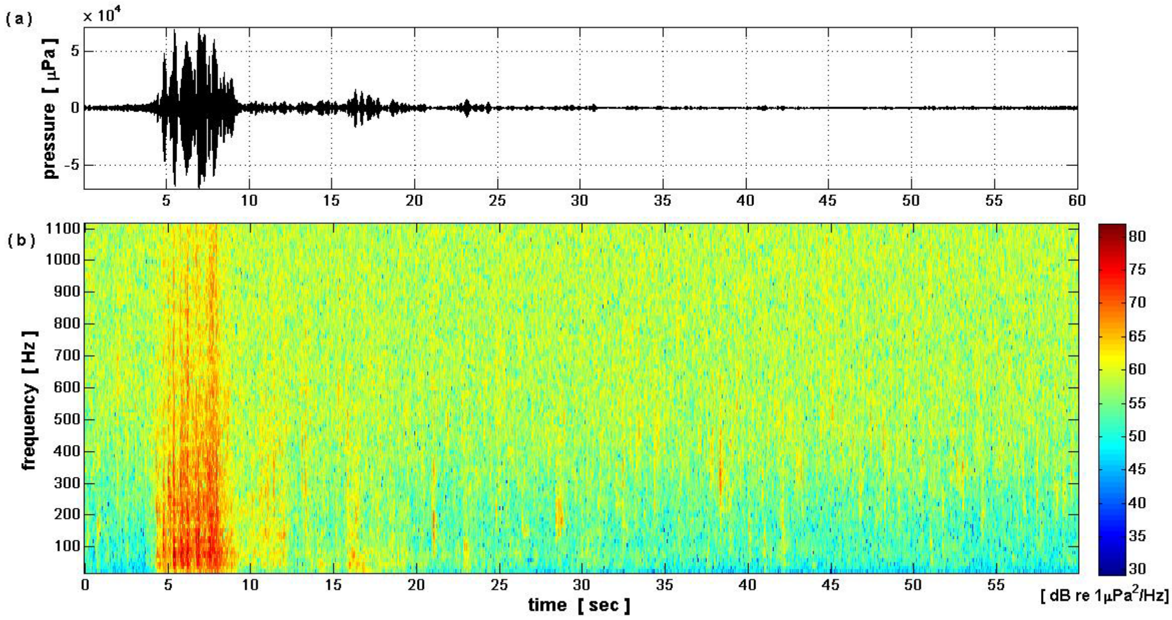

Fig. 2 Example of a one-minute noise pressure time series (after bandpass filtering in the frequency range [28 1,118] Hz) containing the large event of the calving glacier (a) and its spectrogram (b).

As a next step, histograms of the noise spectrum level values averaged over 1-minute intervals were calculated and the most suitable fitting curves of the obtained distribution were established and its statistical parameters were estimated. In most cases, obtained distributions came from family of generalized extreme value (GEV) distributions [9] with a different shape K, scale σ, and location μ parameters. For each one-minute long time interval, statistical distributions obtained in this way were compared with the theoretical Gaussian distribution with the same expectation and standard deviation parameters. In the last step, the significant differences between two distributions (real and theoretical) were calculated.

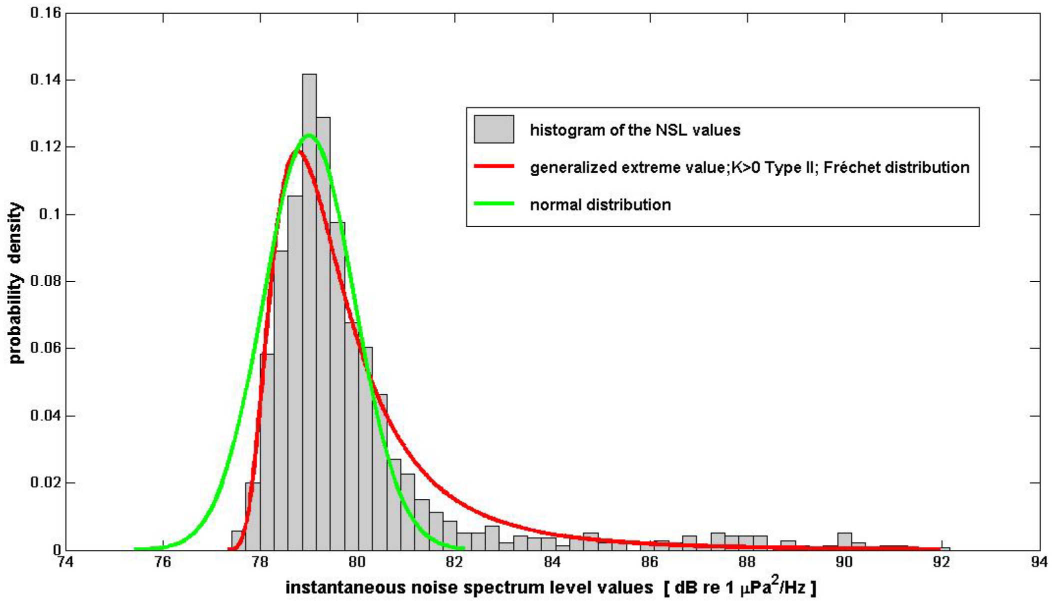

Fig.3 Histogram of the instantaneous noise spectrum level values [dB re 1μPa^2/Hz], with generalized extreme value (red) and normal (green) probability density function fitting curves.

We hypothesise that the long-tail part of the distribution contains information on individual transients in the noise time series which are associated with calving and cracking events. In order to distinguish high-energy spectral components of non-Gaussian origin, the 0.9th quantile of the generated normal distribution was determined as a threshold value. In each of the one-minute noise time series, the subsamples corresponding to the noise spectral level values higher than the chosen threshold value were separated and rejected - in such a way we constructed a new set of data samples which should not include a "tail". The one-minute averaged noise spectrum levels of original ambient noise (blue curve) and spectrum without components of non-Gaussian origin (red curve) are presented in Fig.4. It should be noted that Figure 4 shows levels for the calving event higher than on Figure 1. This comes from looking at two different things: Figure 1 shows 20-minute averages of analyses of 1-second segments, whereas Figure 4 shows analyses of 1-minute segments.

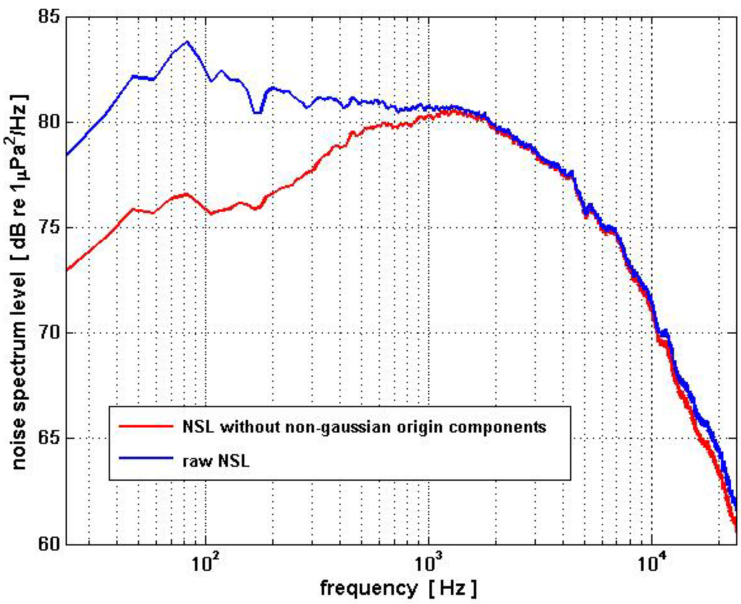

Fig.4. Comparison of one-minute averaged noise spectrum levels [dB re 1μPa^2/Hz] of original ambient noise including the big calving glacier event (blue curve) and noise spectrum level without components of non-Gaussian origin (red curve).

The same procedure was applied for all one-minute long datasets. The result of calculating the difference between the original NSLs and the "cleaned" NSLs is demonstrated in Fig.5.

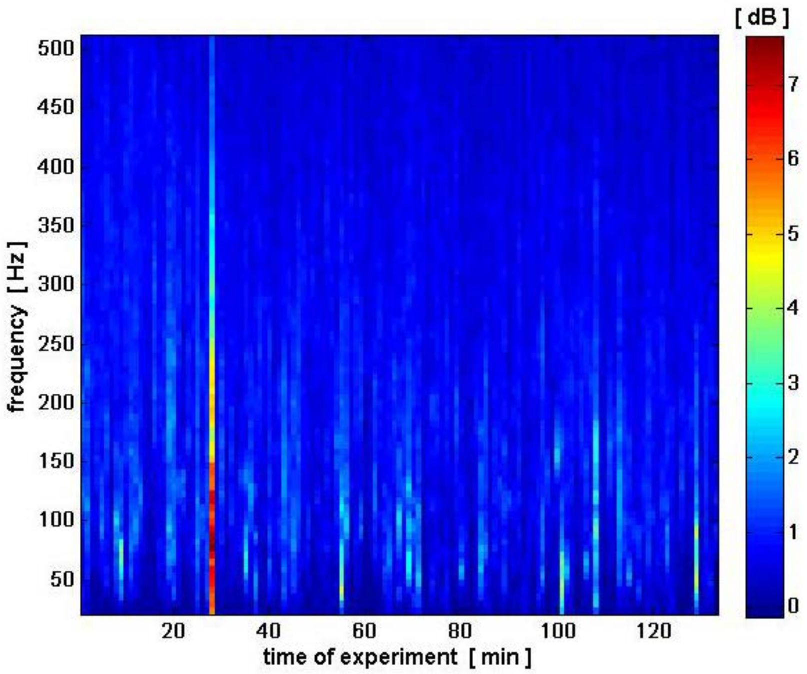

Fig.5.Differences between the original and "cleaned" noise spectral levels in [dB] for the entire ~2 hours measurements.

After 28 minutes of recording, the most significant differences in NSLs reached up to 7.5 dB, which indicates the moment of the big calving event. Additionally, at least 9-10 "smaller" events with a "noticeable" difference ΔNSL > 2.5 dB are observed.

4 CONCLUSIONS

The proposed algorithm confirms the hypothesis that, at low frequencies, the probability density distribution of the ambient noise significantly differs from the normal distribution and can give clues for identification of calving and cracking glacier events. We had a priori assumed the 0.9^{th} quantile of the theoretical normal distribution as a threshold value. Small imperfections are observed in the spectrum after the "cleaning" process (red curve - Fig.4), namely two localised peaks at frequencies close to 50 Hz and 80 Hz. They might result from the selection of this threshold value. They are more likely however to be associated with separate physical processes. Closer examination of the differences between the original and "cleaned" NSLs (Fig.5) show they correspond to elevated levels at all frequencies between 50 Hz and 80-100 Hz approximately, for short times (minute-scale). It is therefore important to also look at how these events unfold in time, and whether they might for example be associated with cracking within the glacier. Further modelling of sound propagation in the entire experimental area should enable localisation of these acoustic sources, and therefore their character and diversity. Comparison with other acoustic measurements obtained during the 2009 Arctic expedition, in other fjords and with different settings, will also help further assess how these "smaller" events are likely to be typical of physical processes within the glaciers.

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